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ELECTROSTATIC TESTING OF THIN PLASTIC MATERIALS

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## ABSTRACT

Ten thin plastic materials (Velostat, RCAS 1200, Llumalloy, Herculite 80, RCAS 2400, Wrightlon 7000, PVC, Aclar 22A, Mylar, and Polyethylene) were tested for electrostatic properties by four different devices: (1) The static decay meter, (2) the manual triboelectric testing device, (3) the robotic triboelectric testing device, and (4) the resistivity measurement adapter device.

The static decay meter measured the electrostatic decay rates in accordance with the Federal Test Method Standard 101B, Method 4046. The manual and the robotic triboelectric devices measured the triboelectric generated peak voltages and the five-second decay voltages in accordance with the "criteria for acceptance standards" at Kennedy Space Center. The resistivity measurement adapter measured the surface resistivity of each material.

An analysis was made to correlate the data between the four testing devices. For the materials tested, the pass/fail results were compared for the 4046 method and the triboelectric testing devices. For the limited number of materials tested, the relationship between decay rate and surface resistivity was investigated as well as the relationship between triboelectric peak voltage and surface resistivity.

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## 1. INTRODUCTION

Electrostatics is the oldest form of electrical phenomena known, first recorded in 1600 by William Gilbert in a treatise entitled, "De Magnete." Electricity was derived from the Greek word for electron (amber in Greek) and triboelectric comes from the Greek word "tribein" which means "to rub." Today, electrostatics is probably the least understood and the hardest to control of all electrical phenomena. Yet, it is very important that we understand and control it. Why? (1) Charge buildup, if present in an explosive atmosphere, can cause a spark discharge, resulting in an explosion. (2) Charge buildup, if present near sensitive electronic components, can cause electronic upset and therefore product failure. (3) Charge buildup promotes the accumulation of dust and dirt which could prove detrimental during further processing of a product. (4) Charge buildup is a hazard to workers doing critical jobs, often surprising a worker with an electrical shock, resulting in an accident.

## 2. PURPOSE

The purpose of this study was to test the electrostatic properties of thin plastic materials. Materials tested were RCAS 1200, RCAS 2400, Llumalloy, Velostat, PVC, Polyethylene, Mylar, Wrightlon 7000, Herculite 80, and Aclar 22A. The manual triboelectric device and the robotic triboelectric device (both developed at NASA's Kennedy Space Center, Materials Science Lab) as well as the static decay meter, Model 406C (produced by Electro-Tech Systems for the Federal Test Method Standard 101B, Test Method 4046) were used to measure electrostatic buildup rates, peak voltages, and decay rates for each material. The resistivity adapter Model 6105, produced by Keithley, was used to determine the resistivities of the materials.

An additional purpose of this study was to correlate the triboelectric data with the Method 4046 and to investigate the relationship between charge generation (or charge decay rate) and surface resistivity.

## 3. INSTRUMENTATION USED

Electrostatic testing of thin plastic materials was performed by the manual triboelectric device, the robotic triboelectric device, the static decay meter, and the resistivity measurement adapter.

### 3.1 THE MANUAL TRIBOELECTRIC TEST DEVICE

The manual triboelectric test device (see Figures 1 and 2) consists of a grounded aluminum frame with two cutouts in the front face plate. The lower right cutout houses the static detector head (Keithley Model 2501) whose output is electrically fed to a solid state electrometer (Keithley Model 610). The upper left cutout is for the rubbing wheel used to generate the triboelectric charge. The rubbing wheel is connected to a 1/8 HP electric drive motor. A manual control lever is used to slide the motor/rubbing wheel combination forward so that the teflon felt rubbing wheel surface makes intimate contact with a static free (de-ionized) test specimen. The pressure between the rubbing wheel and the test specimen is 3 pounds. The rubbing wheel has an angular velocity of 200 rpm. The test specimen is continuously rubbed for precisely 10 seconds. After being rubbed, the test specimen falls in front of the static detector head. The voltage sensed by the detector head is fed into a Nicolet Model 4094 digital oscilloscope for digital storage on a floppy disk and visual display on the oscilloscope screen.

### 3.2 THE ROBOTIC TRIBOELECTRIC TEST DEVICE

The complete robotic device (see Figures 3 and 4) consists of a sample holding carrousel, a robotic arm, a bar code reader, a de-ionizer, a rub wheel, a pneumatic sample transport system, a detector system, a data receiving/computing system, a manual control station, and an overall computer control system.

The metal carrousel has a diameter of four feet and holds 96 eight inch square samples. The robotic arm can process samples at a rate of 47 samples per hour. The samples are first identified by a bar code, then de-ionized for 10 seconds. From the de-ionizer, the robot arm places the sample into a pneumatic sample transporter system. The sample is rubbed by a flat teflon felt rubbing wheel for 10 seconds at a constant speed of 200 rpm with a rubbing force of 3 pounds. After the rubbing, the pneumatic transporter slides the sample to a position directly in front of an electrostatic detecting head (Keithley Model 2501). The electrostatic charge buildup and charge decay is monitored by the detecting head which is connected to a solid state electrometer (Keithley Model 610C). The electrometer output, an electrostatic voltage proportional to the electrostatic charge, is directed into a digital storage oscilloscope (Nicolet Model 4049A) for digital storage on a floppy disk and displayed on the Y axis versus time.

Additional information is fed into the oscilloscope for storage and is displayed from a computer (Hewlett Packard Model HP 85). The computer is used to control the total operation in the automatic mode.

After a 10-second observation of the electrostatic buildup and discharge, the sample is picked up by the robot arm and returned to its position in the sample carousel. The next sample is then removed from the carousel and initiated into the test sequence.

The robotic triboelectric testing device is housed in an environmental chamber which is designed to maintain any selected environment from 20% to 95% relative humidity and any selected temperature from 40° to 100°F.

### 3.3 THE STATIC DECAY METER

The static decay meter (see Figure 5), Model 406C (Electro-Tech Systems, Inc.) is the latest version of static decay measuring equipment. It is a complete system available for measuring the electrostatic properties of materials in accordance with Federal Test Method Standard 101B, Method 4046 - Electrostatic Properties of Material. The system also meets the requirements of MIL-B-81705B, NFPA Code 56A and the latest EIA (Electronic Industries Association) specifications for antistatic materials.

The Model 406C static decay meter is designed to test the electrostatic properties of materials by measuring the time required for a charged test sample to discharge to a known, predetermined cutoff level. Three manually selected cutoff thresholds at 50% (half-life), 10% (NFPA-56A), and 0% (MIL-B-81705B) of full charge are provided. Samples are charged by an adjustable 0 to  $\pm 5$  KV high voltage power supply. The sample is contained in a special Faraday Cage that enables the system to make a true electrostatic (non-contact) measurement of the charge on the sample.

### 3.4 THE RESISTIVITY MEASUREMENT ADAPTER

The resistivity measurement adapter (see Figure 6) Model 6105 (Keithley) is a guarded test device for measuring volume and surface resistivities of materials when used with a regulated power supply (Keithley Model 247) and an electrometer (Keithley Model 610C). The complete system is capable of measuring volume resistivity from  $10^3$  to  $3 \times 10^{19}$  ohm-cm and surface resistivity from  $10^3$  to  $5 \times 10^{18}$  ohms per square, in accordance with procedures of the American Society for Testing and Materials. The adapter can accommodate samples up to 4 inches in diameter and 1/4 inch thick with excitation voltages up to 1000 volts.

For this experimentation only surface resistivities were found. The value of the surface resistivity was calculated via the following equation:

$$\rho = \frac{53.4V}{I} \text{ [ohms per square]}$$

where  $\rho$  is the surface resistivity of the sample, V is the applied voltage from the power supply in volts, and I is the current reading from the electrometer in amperes. Measurement accuracy depends primarily upon the accuracy of the voltage source and the electrometer.

#### 4. CRITERIA FOR ACCEPTANCE STANDARDS

##### 4.1 KSC ELECTROSTATIC STANDARD FOR THE MANUAL AND THE ROBOTIC TRIBOELECTRIC DEVICES

Materials are considered acceptable for use at KSC if the electrostatic voltage generated by the triboelectric devices decays below 350 volts in 5 seconds.

##### 4.2 FEDERAL TEST METHOD STANDARD 101B, METHOD 4046 - ELECTROSTATIC PROPERTIES OF MATERIALS

National Fire Protection Association (NFPA) code 56A: After the sample has received its maximum charge from the application of 5000 volts, the time for the indicated sample potential to drop to 10% of its maximum values shall not exceed 1/2 second.

The Military (MIL-B-81705B) and the Electronic Industries Association specification: After the sample has received its maximum charge from the application of 5000 volts, the time for the indicated sample potential to drop to 0% of its maximum value shall not exceed 2.00 seconds.

#### 5. DESIGN OF THE EXPERIMENT

The ten materials tested for electrostatic properties were RCAS 1200 (polyethylene), RCAS 2400 (nylon), Llumalloy (polyester), Velostat (polyethylene), PVC (vinyl), untreated Polyethylene (polyethylene), untreated Mylar (polyester), Wrightlon 7000 (nylon), Herculite 80 (vinyl coated fabric), and Aclar 22A (PCTFE).

Nine samples of each material were tested for peak voltage and 5-second decay voltage with the robotic triboelectric device. Five samples of each material were tested for peak voltage and 5-second decay voltage via the manual triboelectric device. Either five or ten samples of each material were tested for 10% and 0% decay times with the static decay meter (method 4046). Ten samples of each material were tested for surface resistivity by means of the resistivity measurement adapter. The tests were run in an environmental chamber at a temperature of  $75^{\circ}\text{F} \pm 3^{\circ}\text{F}$  and a relative humidity of  $45\% \pm 5\%$ .



## 6. ANALYSIS

Table 1 is a summary of the 4046 method for the ten materials. It depicts that Velostat, RCAS 1200, Llumalloy, and Herculite 80 passed both the NFPA Code 56A requirements (10%) and the military and EIA requirements (0%) while RCAS 2400, Wrightlon 7000, PVC, Aclar 22A, and Polyethylene failed both requirements.

Table 2 is a summary of the manual triboelectric testing for the ten materials. Velostat, RCAS 1200, Llumalloy, Herculite 80, RCAS 2400, and Wrightlon 7000 passed the KSC acceptability criterion of decaying below 350 volts in 5 seconds, while the PVC, Aclar 22A, Mylar, and Polyethylene failed the test.

The pass/fail results of the manual triboelectric testing (Table 2) agree with the method 4046 results (Table 1) for all materials except RCAS 2400 and Wrightlon 7000. These two materials passed the manual triboelectric testing but failed the 4046 method. However, a closer examination of the manual triboelectric testing data of RCAS 2400 reveals that the decaying mean voltage at 0.5 seconds (the 10% criterion for the Method 4046) is 3322 volts, 2307 volts above 1017 volts (10% of the 10166 volt peak voltage); thereby, failing the 4046 10% criterion. In other words, using the 10% criterion, RCAS 2400 failed both the manual triboelectric testing and the 4046 method. Further examination of data for RCAS 2400 shows that it fails both the manual triboelectric testing and the method 4046 using the 0% criterion. Likewise, manual triboelectric data for Wrightlon 7000 fails both the 10% and 0% criteria as it did for the Method 4046. See notes at the bottom of Table 2.

Table 3 is a summary of the robotic triboelectric testing for the ten materials. It reveals that Velostat, RCAS 1200, Llumalloy, and Herculite 80 passed KSC acceptability criterion of decaying below 350 volts in 5 seconds, while RCAS 2400, Wrightlon 7000, PVC, Aclar 22A, Mylar, and Polyethylene failed the test. The pass/fail results of the robotic triboelectric testing (Table 3) agree with both the method 4046 results (Table 1) and the manual triboelectric testing results (Table 2 using the 10% and 0% criteria).

A comparison between Table 3 and Table 2 shows that for each material the peak voltage generated by the robotic triboelectric device is higher than the peak voltage generated by the manual triboelectric device. The average peak voltage is 10304 volts for the robotic triboelectric device and 5587 volts for the manual triboelectric device. Likewise, the 5-second voltage for the robotic device is higher than for the manual device in every case, except where both decayed to 0 volts. The average 5-second voltage is 5792 volts for the robotic device and 3059 for the manual device. The ratio of the 5-second voltage to the

peak voltage for the robotic device is 0.56 and for the manual device is 0.55 revealing that the values are very close. One would expect this since the decay curves are similar. The reason the robotic triboelectric device generates higher peak voltages than the manual triboelectric device is because the teflon rubbing wheel impacts the sample materials with a high force in the robotic testing while the teflon rubbing wheel in the manual system is gently brought forward by the operator to make contact with the sample materials.

Table 4 is a summary of the resistivity for the ten materials. Using the classifications found in NASA's "Electrostatic Discharge Control Information Manual," (Document D-TM-82-1), Velostat is classified as a conductive material; RCAS 1200, Llumalloy, Herculite 80, RCAS 2400, and Wrightlon 7000 are classified as antistatic materials; PVC, Aclar 22A, Mylar, and Polyethylene are classified as insulative materials. Table 4 reveals that any material having a resistivity of greater than  $10^{12}$  ohms per square fails the 4046 method and any material having a resistivity of greater than  $10^{15}$  ohms per square fails the manual triboelectric testing. As depicted in Graph 1 (Decay Time Versus Resistivity for the Method 4046), Graph 2 (Decay Time Versus Resistivity for the Manual Triboelectric Testing Device), and Graph 3 (Decay Time Versus Resistivity for the Robotic Triboelectric Testing Device), there appears to be a relationship between decay rate and resistivity for the materials in this study, i.e., the higher the resistivity of the material, the slower the decay rate. However, Graph 4 (Peak Voltage Versus Resistivity for the Manual Triboelectric Device) reveals that for this study, resistivity is not related to peak voltage, i.e., those materials that generate high electrostatic tribo-charges are not necessarily those materials that have high resistivities. Graph 5 (Peak Voltage Versus Resistivity for the Robotic Triboelectric Device) depicts the same information as Graph 4.

A comparison of the variances of the data collected by the method 4046, the manual triboelectric testing, the robotic triboelectric testing, and the resistivity measurement adapter is revealed in Tables 1, 2, 3, and 4 by the ratio of the standard deviation to the mean,  $\sigma/\bar{x}$ . The variance is least for the Method 4046 (0.17 for both 10% and 0% criteria), while the variance for the resistivity measurements is the greatest (0.57). Variances for the manual triboelectric testing is 0.29 for peak voltages and 0.38 for the five-second voltages. Variance for the robotic triboelectric testing is 0.25 for the peak voltages and 0.40 for the five-second voltages.

## 7. CONCLUSIONS

The pass/fail results for the Method 4046, the manual triboelectric testing, and the robotic triboelectric testing agree. Sample preparation and data collection is much faster for the Method 4046 than for the triboelectric testing devices. The variance is smaller for Method 4046 than for either triboelectric testing or the resistivity measurements. Also, it is possible via the oscilloscope to record applied charge build-up rates (remember it is an applied potential like one found on a capacitor plate, not a triboelectric charge) as well as charge decay rates with the Method 4046. A major disadvantage is that certain insulative materials, e.g., high resistivity materials like Mylar, Aclar, and Polyethylene, are unable to generate a charge using this technique (or at best takes a very long time).

The triboelectric test methods are important and recommended because they can identify a material which possesses a high electrostatic charging tendency. Even though this material might have passed both the 4046 method (both the 10% and 0% criteria) and the triboelectric tests (voltage drops to less than 350 volts in 5 seconds), it may still be considered a hazardous material from an electrostatic discharge viewpoint. An example of this is Herculite 80. Even though Herculite 80 passed both the 4046 method and the triboelectric tests, it might be hazardous under certain conditions because of its tribo-charge generating potential. It developed 3193 volts by the manual triboelectric testing device and 7820 volts by the robotic triboelectric testing device. By placing a tribo-charged Herculite 80 sample close to a conductor, it could induce an opposite charge on the conductor, which in turn could discharge via a spark, causing an explosive or hazardous situation. In other words, a major advantage triboelectric tests have over the 4046 method is that they evaluate two distinct electrostatic properties of a material: (1) The material's capability to develop a turbo-charge, which is shown by the peak triboelectric voltage generated and (2) the material's ability to discharge the surface electrical charge to a ground, which is depicted by a decay curve. The 4046 method can evaluate only (2) above; it cannot evaluate (1), the material's ability to generate a tribo-charge. The resistivity measurements evaluates neither (1) or (2) above.

Triboelectric testing by the robotic device is advantageous because of its robotic nature, i.e., when operating correctly, it allows rapid testing and recording of data on a continuous basis without close supervision.

As discussed in the analysis section of this paper, there appears to be a relationship between surface resistivity and

decay rate for those materials tested, i.e., materials with high surface resistivity have long decay rates and materials with low surface resistivity have short decay rates. On the other hand, there appears to be little or no relationship between surface resistivity and electrostatic charging tendency, i.e., those materials with high surface resistivity do not necessarily have high electrostatic charging tendency and those material with low surface resistivity do not necessarily have low electrostatic charging tendency.

Sample preparation and data collection are fast for the surface resistivity measurements. The results for Llumalloy were rejected because when the test is applied to non-homogeneous materials with different resistivity layers, a field suppression effect can cause ambiguous measurements.

## 8. RECOMMENDATIONS

The following non-priority recommendations are made:

- a. Establish better calibration methods for the triboelectric testing devices and the resistivity measurement adapter.
- b. Investigate the sample grounding systems for the robotic and the manual triboelectric devices to establish if equivalent grounding systems for the two devices are desirable. At present the sample of the robotic device is grounded by a contact point while the sample of the manual device is grounded by the total holding frame.
- c. Establish equivalent peak voltages for the same samples on both the robotic and manual triboelectric devices by making the impact force between the rubbing wheel and the sample equivalent for the two devices.
- d. Test more and different materials with all four testing devices in order to establish a larger data base; thereby correlating and gaining confidence that the testing devices are making the same decisions in regard to pass/fail of materials.
- e. Continue to test with the triboelectric devices because they are the only methods that have the ability to reveal the tribo-charge generating capacity of a material.

- f. Conduct more tests with all four devices varying the relative humidity but keeping the temperature constant, i.e., are peak voltage, decay rate, and resistivity dependent on humidity?
- g. Conduct more tests with all four devices varying the temperature but keeping the relative humidity constant, i.e., are peak voltage, decay rate, and resistivity dependent on temperature?
- h. Continue to test materials via the resistivity measurement adapter in order to discover (a) those unique materials which have high surface resistivity but no or only insignificant charging tendency or (b) those rare materials which have low surface resistivity but possess a high charging tendency. This testing can be accomplished by using the resistivity measurement adapter in conjunction with the triboelectric testing devices.
- i. Modify testing devices where necessary and design experiments which will decrease the variances in the data, i.e., decrease the standard deviations, thereby ensuring the reproducibility of results.
- j. Test more samples by each test method in order to increase the data base and establish the reliability of the test method and the validity of the data, i.e., show that each test method passes the same materials and fails the same materials with the same degree of reliability and validity.

## 9. GLOSSARY

### 9.1 CONDUCTIVE MATERIAL

Electrostatic discharge (ESD) protective material having a surface resistivity of  $10^5$  ohms per square maximum.

### 9.2 STATIC DISSIPATIVE MATERIAL

ESD protective material having a surface resistivity greater than  $10^5$  but not greater than  $10^9$  ohms per square.

### 9.3 ANTI-STATIC MATERIAL

ESD protective material having a surface resistivity greater than  $10^9$  but not greater than  $10^{14}$  ohms per square.

#### 9.4 INSULATIVE MATERIAL

Material having surface resistivity greater than  $10^{14}$  ohms per square.

#### 9.5 NON-ANTISTATIC MATERIAL

A non-antistatic material does not permit electrons to flow across the surface. However, electrons can be removed or added triboelectrically to produce a positive or negative charge on the material. When this occurs, the sample is said to have an initial charge. As soon as the sample is placed in the test electrodes, this initial charge is detected by the Electrostatic Voltmeter which is connected to the static decay meter, Model 406C. If the entire sample is non-antistatic, then when  $\pm 5$  KV is applied the sample will not conduct on a charge and when the sample is grounded (depress TEST button) the sample will not bleed off the charge. When the 5KV is applied, the SAMPLE CHARGE Meter will read the algebraic sum of the initial sample charge and the free air value (1,500 volts).

#### 9.6 PORTIONAL NON-ANTISTATIC

If only a portion of the sample is non-antistatic, then the SAMPLE CHARGE Meter of the static decay meter, Model 406C, will read an initial charge (not a calibrated value, however, because the "dead" spot occupies only a portion of the field in view of the electrostatic Voltmeter sensor). When the 5KV is applied, the SAMPLE CHARGE Meter will read the algebraic sum of the initial charge and the applied 5KV. When the TEST button is depressed the sample will bleed off the applied charge and decay down to the initial charge. The initial charge has the ability to move or migrate into a "dead" spot or other position on the sample.

#### 9.7 MARGINALLY ANTISTATIC MATERIAL

Marginally antistatic materials with very long decay times, and therefore, very long charging times, can be evaluated with the static decay meter by measuring the amount of charge the sample accepts over some fixed period of time. The accepted charge in this case is the charge conducted on the sample after the 5KV has been applied (initial charge plus free air value) to the value. The more charge accepted within the established time period, the better the antistatic properties of the material.

#### 9.8 DECAY TIME

The time for a static charge to be reduced to a given percent of the charge's peak voltage.

## 9.9 SURFACE RESISTIVITY

The surface resistivity is an inverse measure of the conductivity of a material and equal to the ratio of the . potential gradient to the current per unit width of the surface, where the potential gradient is measured in the direction of current flow in the material. (Note: Surface resistivity of a material is numerically equal to the surface resistance between two electrodes forming opposite sides of a square. The size of the square is immaterial. Surface resistivity applies to both surface and volume conductive materials and has the value of ohms per square).

## 9.10 TRIBOELECTRIC EFFECT

The generation of static electricity caused by rubbing two substances is called the triboelectric effect. In addition to actually rubbing two different substances, substantial electrostatic charges can also be generated triboelectrically when two pieces of the same material, especially common plastics, in intimate contact are separated. This phenomenon occurs when separating the sides of a plastic bag.

## 9.11 FREE AIR MEASUREMENT

When using the static decay meter; Model 406C, the free air measurement is the free air field caused by the charge on the electrodes and is approximately 1500 volts. That is, when 5,000 volts are applied to the electrodes with no sample in place, the electrostatic voltmeter will read 1,500 volts.

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TABLE 1  
METHOD 4046

MATERIAL	TIME FOR 10%				TIME FOR 0%			
	MEAN $\bar{X}$ (SEC)	STD. DEV. $\sigma$ (SEC)	$\frac{\sigma}{\bar{X}}$	PASS/ FAIL	MEAN $\bar{X}$ (SEC)	STD. DEV. $\sigma$ (SEC)	$\frac{\sigma}{\bar{X}}$	PASS/ FAIL
VELOSTAT	<0.01	0.00	0.00	P	<0.01	0.00	0.00	P
RCAS 1200	0.05	0.02	0.40	P	0.10	0.05	0.50	P
LLUMALLOY-HST								
AL SIDE	<0.01	0.00	0.00	P	<0.01	0.00	0.00	P
POLYESTER SIDE	<0.01	0.00	0.00	P	0.02	0.01	0.00	P
HERCULITE 80	0.40	0.08	0.20	P	1.08	0.18	0.17	P
RCAS 2400	2.29	0.41	0.18	F	5.50	0.91	0.17	F
WRIGHTLON 7000	1.46	0.33	0.23	F	3.30	0.70	0.21	F
PVC	1455	261	0.18	F	1762	203	0.12	F
ACLAR 22A*				F				F
MYLAR*				F				F
POLYETHYLENE*				F				F
AVERAGE			0.17				0.17	

\*CANNOT PUT A CHARGE ON THESE MATERIALS BY METHOD 4046

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TABLE 2  
MANUAL TRIBOELECTRIC TESTING

MATERIAL	PEAK VOLTAGE			FIVE SECOND VOLTAGE			
	MEAN $\bar{X}$ (VOLTS)	STD.DEV. $\sigma$ (VOLTS)	$\frac{\sigma}{\bar{X}}$	MEAN $\bar{X}$ (VOLTS)	STD. DEV. $\sigma$ (VOLTS)	$\frac{\sigma}{\bar{X}}$	PASS/ FAIL
VELOSTAT	110	32	0.29	0	0	0	P
RCAS 1200	74	36	0.49	23	29	1.26	P
LLUMALLOY-HST							
AL SIDE	51	14	0.27	0	0	0	P
POLYESTER SIDE	163	40	0.25	108	51	0.47	P
HERCULITE 80	3193	600	0.19	0	0	0	P
RCAS 2400	10166	977	0.10	50	38	0.76	P*
WRIGHTLON 7000	6184	1061	0.17	0	0	0	P**
PVC	4163	2855	0.69	2310	1726	0.75	F
ACLAR 22A	-22252	1473	0.07	-19596	717	0.04	F
MYLAR	7092	2627	0.37	5764	1943	0.34	F
POLYETHYLENE	8008	3218	0.40	5796	3508	0.61	F
AVERAGE			0.29			0.38	

\*WOULD HAVE FAILED THE METHOD 4046 10% CRITERION ( $\bar{X}$  = 3322 VOLTS,  $\sigma$  = 944 VOLTS).  
WOULD HAVE FAILED THE METHOD 4046 0% CRITERION ( $\bar{X}$  = 348 VOLTS,  $\sigma$  = 155 VOLTS)  
\*\*WOULD HAVE FAILED THE METHOD 4046 10% CRITERION ( $\bar{X}$  = 1796 VOLTS,  $\sigma$  = 658 VOLTS).  
WOULD HAVE FAILED THE METHOD 4046 0% CRITERION ( $\bar{X}$  = 86 VOLTS,  $\sigma$  = 25 VOLTS)

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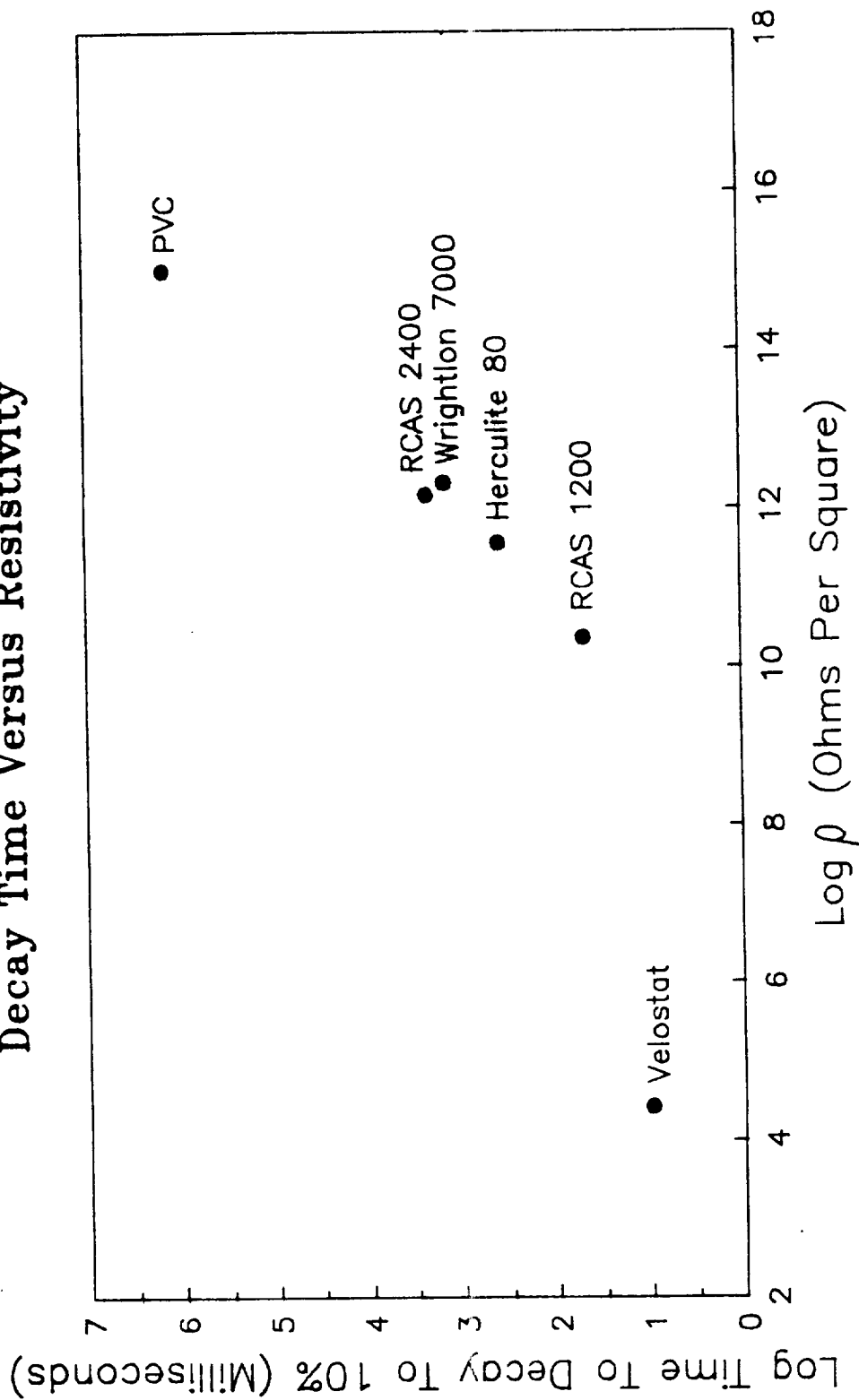
TABLE 3  
ROBOTIC TRIBOELECTRIC TESTING

MATERIAL	PEAK VOLTAGE			FIVE SECOND VOLTAGE			
	MEAN $\bar{X}$ (VOLTS)	STD.DEV. $\sigma$ (VOLTS)	$\frac{\sigma}{\bar{X}}$	MEAN $\bar{X}$ (VOLTS)	STD. DEV. $\sigma$ (VOLTS)	$\frac{\sigma}{\bar{X}}$	PASS/ FAIL
VELOSTAT	2482	153	0.06	0	0	0	P
RCAS 1200	2756	2154	0.78	188	133	0.96	P
LLUMALLOY-HST							
AL SIDE-HST	320	145	0.45	0	0	0	P
POLYESTER SIDE	1407	145	0.45	0	0	0	P
HERCULITE 80	8087	1322	0.16	0	0	0	P
RCAS 2400	12704	3397	0.27	7096	1922	0.27	F
WRIGHTLON /UUU	20887	508	0.02	462	93	0.20	F
PVC	8129	1622	0.20	5047	1279	0.25	F
ACLAR 22A	-24247	-3931	0.16	-22718	-3874	0.17	F
MYLAR*	15153	2971	0.20	13338	3949	0.30	F
POLYETHYLENE	17169	1860	0.11	14896	488	0.03	F
AVERAGE			0.25			0.40	

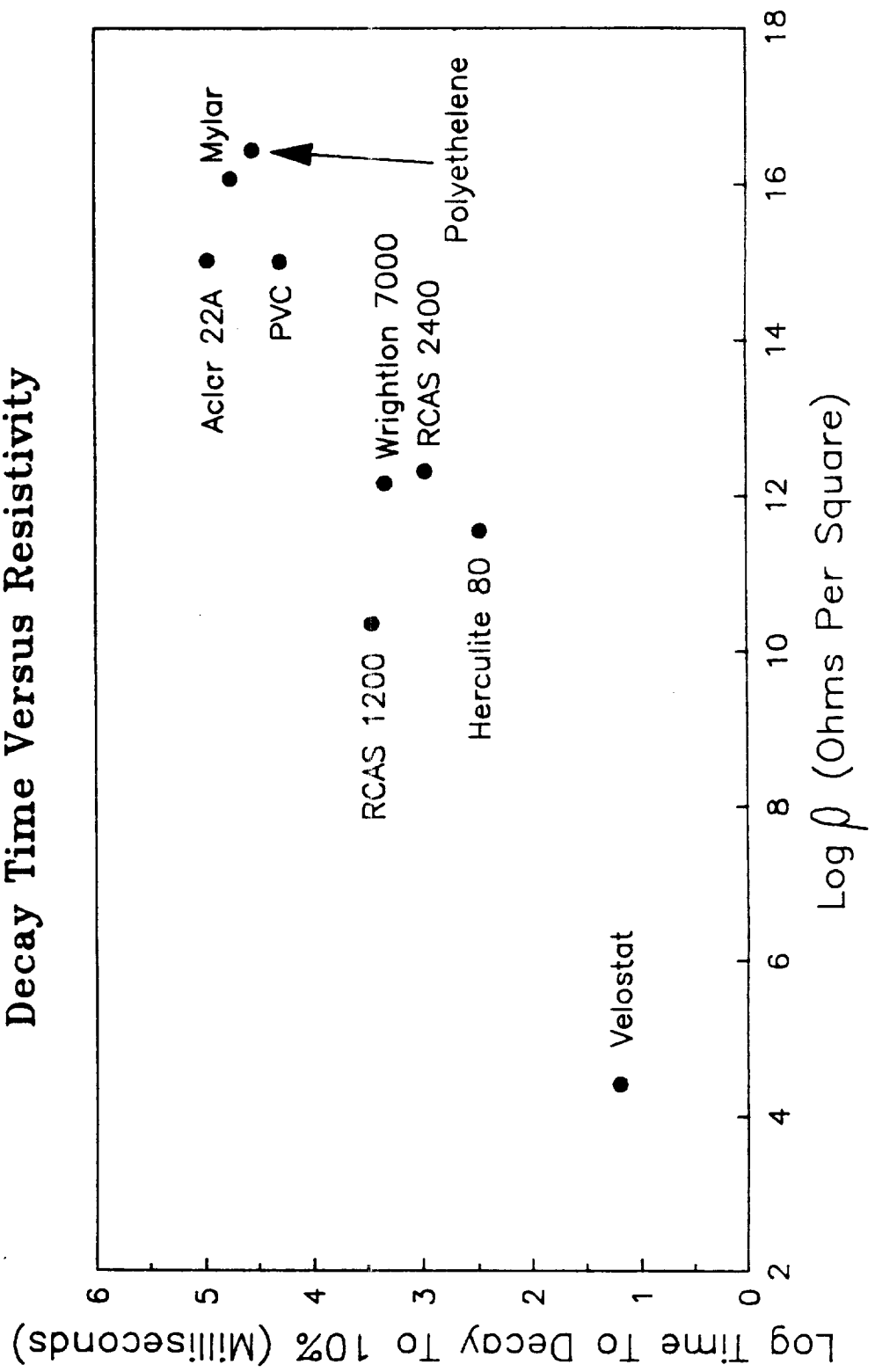
\*SIX MYLAR SAMPLES CHARGED UP NEGATIVE AND THREE CHARGED UP POSITIVE



**Graph 1**  
**Method 4046**  
**Decay Time Versus Resistivity**

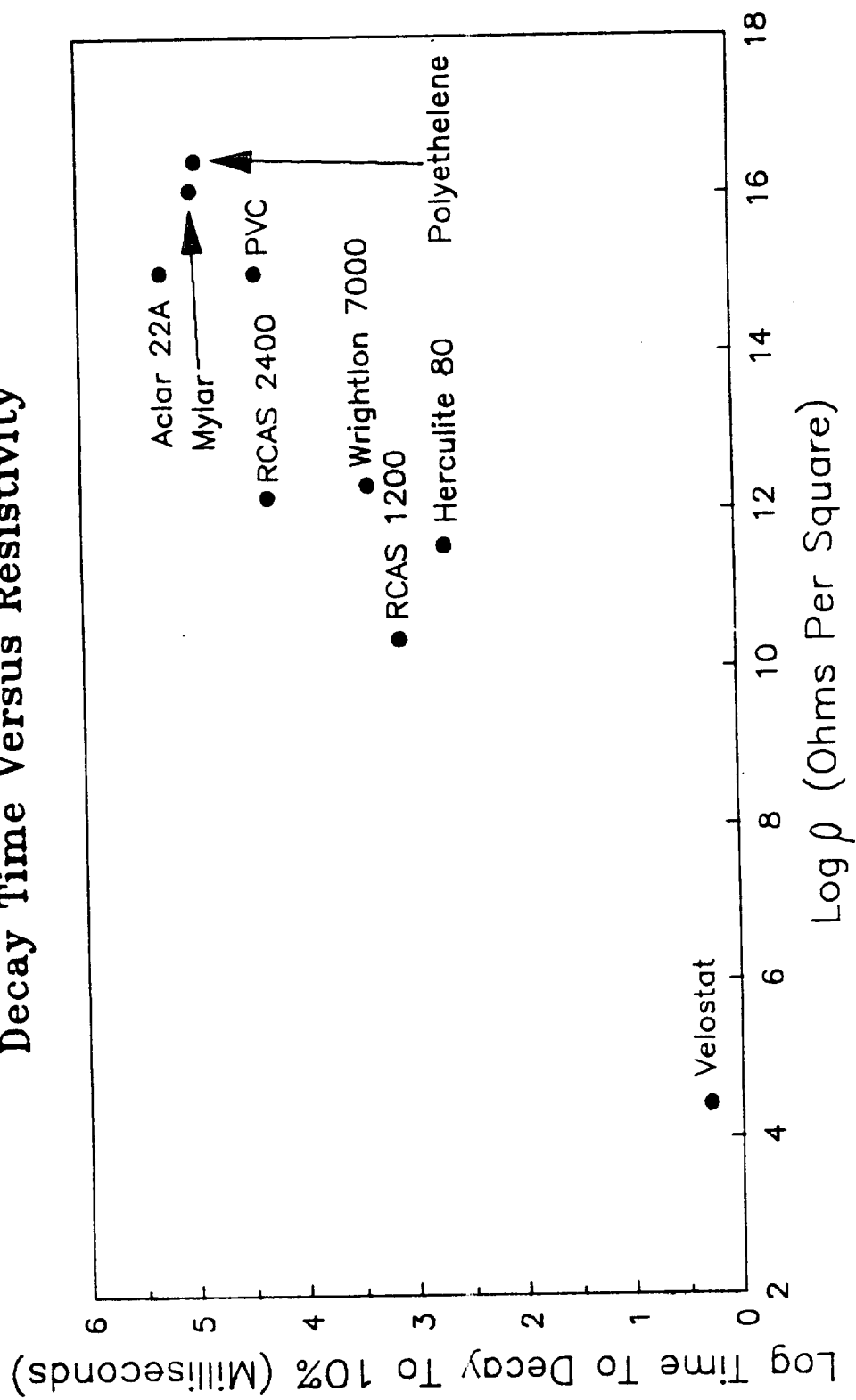


**Graph 2**  
Manual Triboelectric  
Decay Time Versus Resistivity



# Graph 3

Robotic Triboelectric  
Decay Time Versus Resistivity



**Graph 4**  
**Manual Triboelectric**  
**Peak Voltage Versus Resistivity**

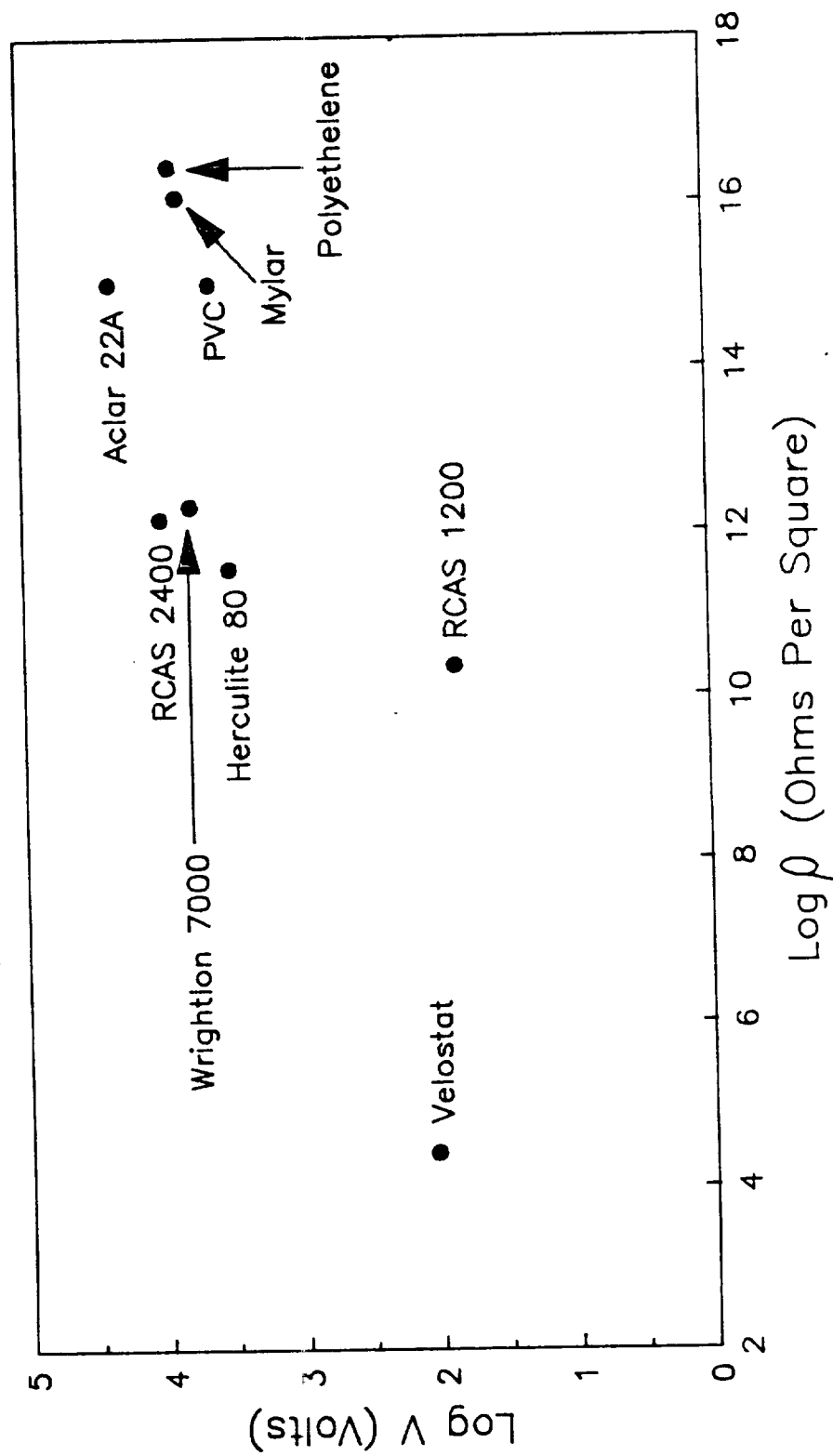




Figure 5

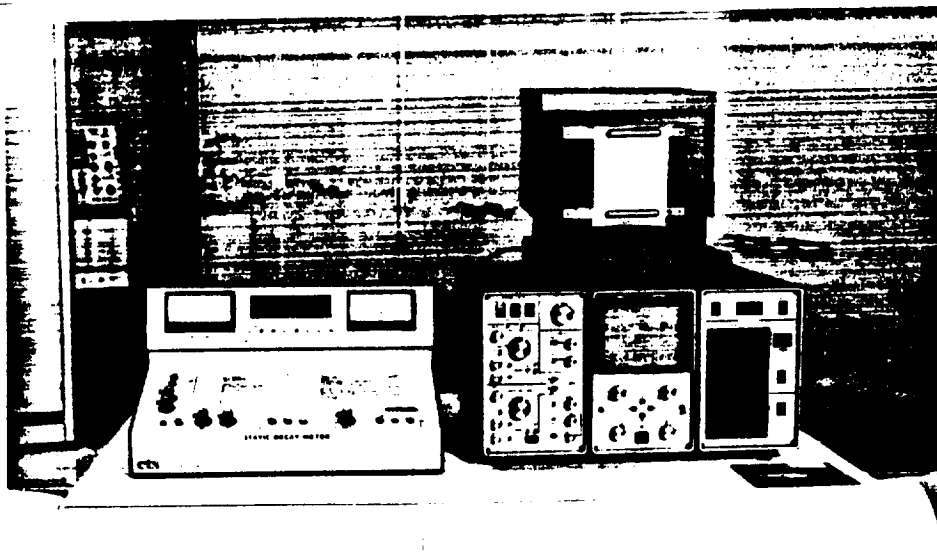
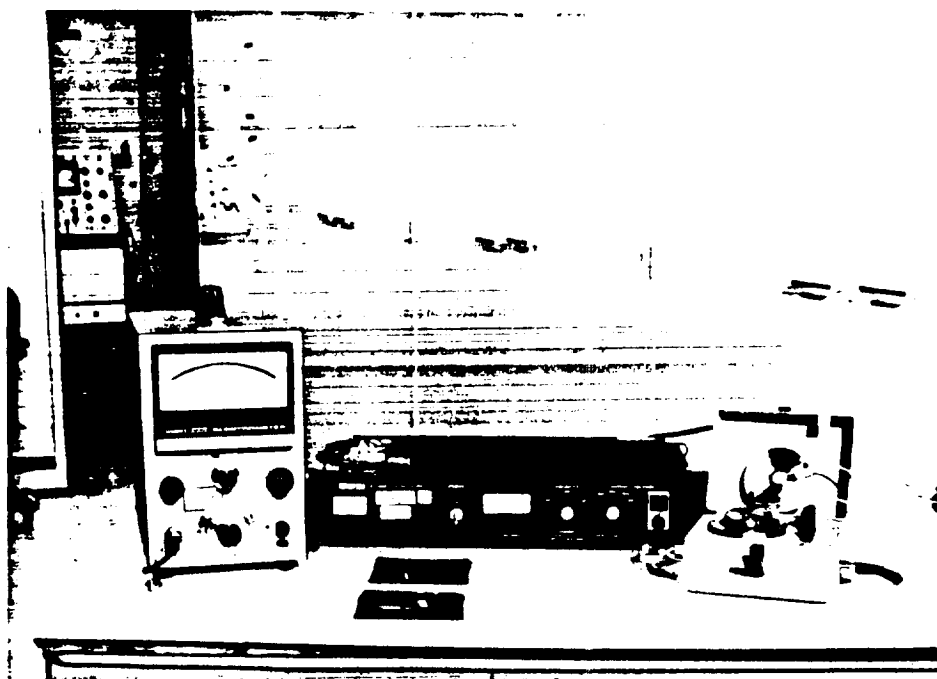


Figure 6



ORIGINAL PAGE IS  
OF POOR QUALITY

Figure 3

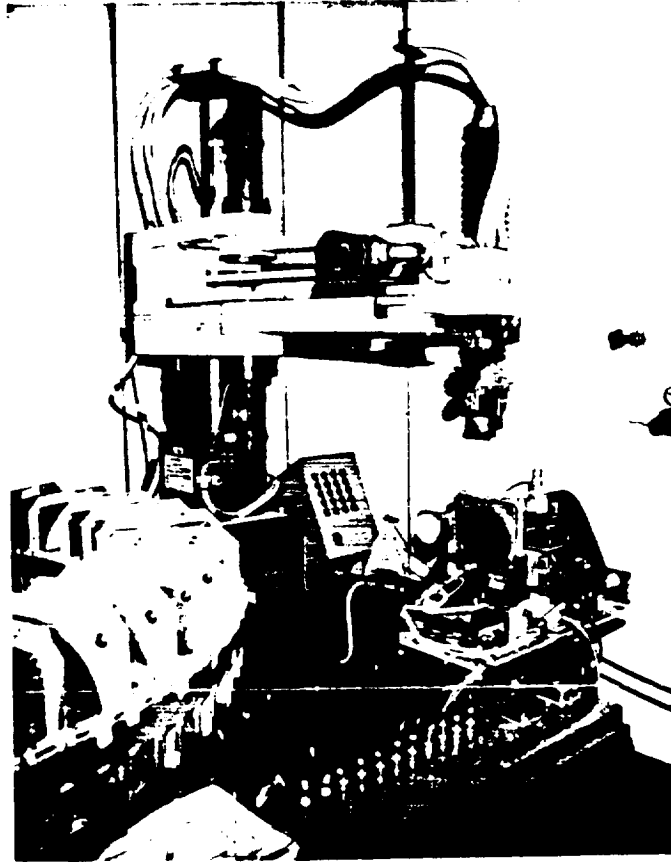
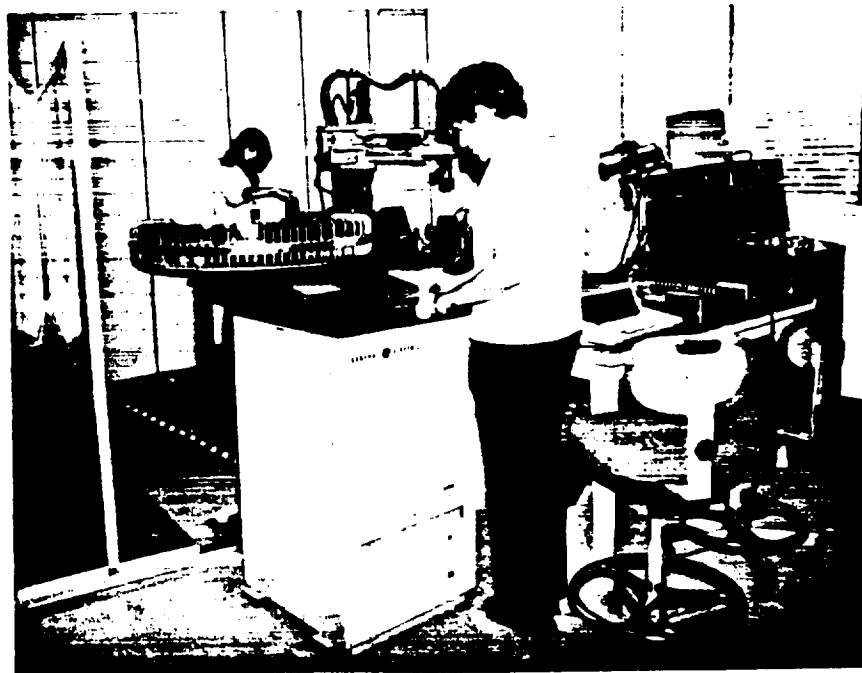


Figure 4



ORIGINAL PAGE IS  
OF POOR QUALITY

Figure 1

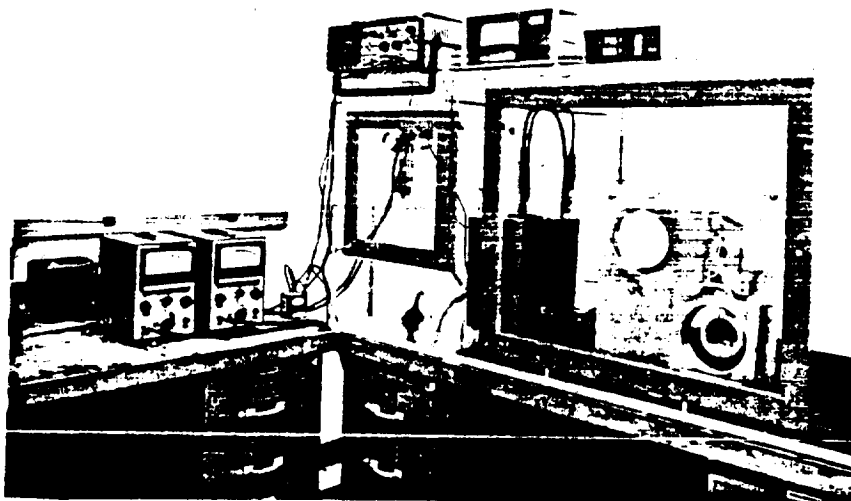
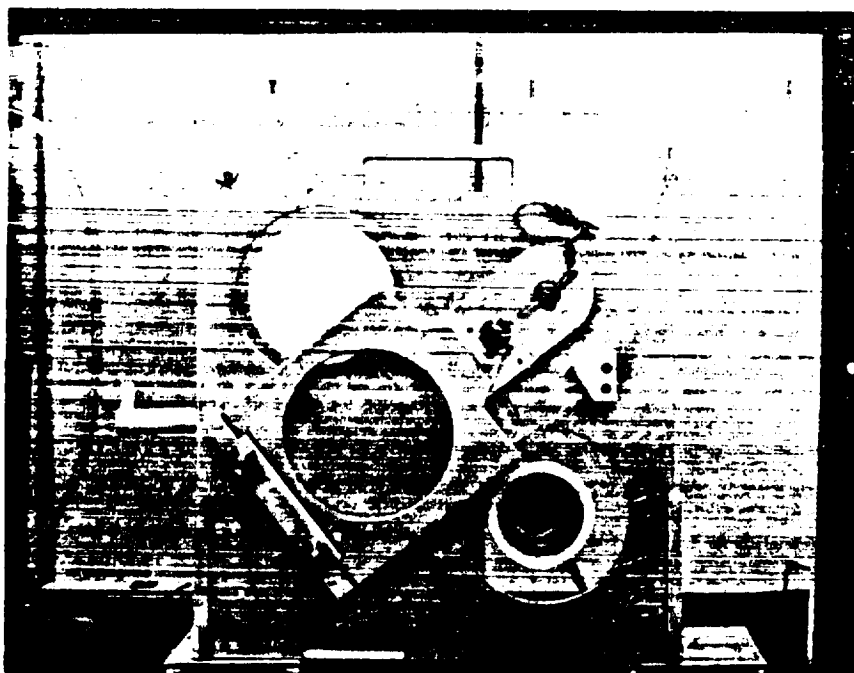


Figure 2



**Graph 5**  
**Robotic Triboelectric**  
**Peak Voltage Versus Resistivity**

